



American Society of  
Agricultural and Biological Engineers

**An ASABE Meeting Presentation**

**Paper Number: 074116**

## Design Considerations for the Construction and Operation of Flour Milling Facilities. Part I: Planning, Structural, and Life Safety Considerations

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**Written for presentation at the  
2007 ASABE Annual International Meeting  
Sponsored by ASABE  
Minneapolis Convention Center  
Minneapolis, Minnesota  
17 - 20 June 2007**

**Abstract.** *Flour milling facilities have been the cornerstone of agricultural processing for centuries. Like most agri-industrial production facilities, flour milling facilities have a number of unique design requirements. Design information, to date, has been limited. In an effort to summarize state of the art design procedures for flour milling facilities constructed in the United States, an overview of accepted standards and procedures has been assembled and discussed. With this paper engineers should become more familiar with specific design considerations for flour milling production facilities and develop appropriate references to expand their knowledge base. Educators may find this paper useful too.*

**Keywords.** Agri-Industry, Concrete, Foundations, FDA, Flour Milling, Grain, Layout, Life-Safety, OSHA, Planning, Steel, Structural Design.

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## Introduction

Flour milling is as old as human history. Ancient farmers used saddle stones or querns to grind their grain into flour. In the middle ages, gristmills were developed that could grind larger amounts of grain into flour. These original mills were powered by wind, water, animals or even humans. Historically, each town had their own mill, and the miller would operate for a portion of the finished flour. This was the hub of each community, and remained that way for centuries. The development of the roller mill in the 1870's started the growth of the modern flour mill and the consolidation of the flour milling industry.

In 1870 there were over 23,000 flour mills in the United States. In 2002, there were estimated to be only 336 operating flour mills, with a total of 11,460 employees (US Census Bureau, 2007). In 2002, 885 million bushels of wheat were ground into approximately 26.5 million tons of flour. There were nearly 7 billion dollars in total revenues for the flour milling industry (US Census Bureau, 2007).

Over time, consolidation has resulted in more technically complex facilities. Today's flour mill integrates the building facility with the process into a comprehensive and efficient structure. Because of this complexity, engineers must have an understanding of multiple technical areas in order to develop and operate functional projects. The purpose of this paper is to discuss modern flour mill design and construction methods. This paper will discuss planning, life-safety considerations, food compliance regulations, and building design and construction. The target audience is agricultural engineering students, academic professionals and practicing engineers.

## Overview of a Flour Milling Facility

The modern flour milling process was developed in the late 1800's with the advent of the modern flour mill. Over the decades improvements have been made to various aspects of the flour milling process, but the major elements of the process have stayed essentially the same since the inception of the roller mill. Particulars of the process are discussed in Rosentrater and Williams (2007). Others have described the complete details of the flour milling process (Ownes 2000 and Posner & Hibbs 2004). Figure 1 shows the main building elements of a typical flour milling process, and Figure 2 shows the layout for a typical flour mill. Figure 3 shows a section of a typical flour mill with some of its major elements. The following paragraphs describe a general overview of the flour milling process.

The flour milling process starts with the receiving and storage of whole grain. Grain is stored in groups of steel or concrete silos laid out very similar to grain elevators. The grain is moved through the cleaning system which is housed in the cleaning tower. A variety of cleaning equipment is housed in the multi-story cleaning tower, and cleaning is done with machinery using air currents, magnets and screens to separate the wheat from stones, sticks, other grains and undesirable elements. Equipment typically consists of separators, destoners, magnets, aspirators and other cleaning machinery. After cleaning, the grain is moved to temporary storage silos (known as clean storage) prior to tempering.

Immediately prior to milling the wheat is moved to tempering bins at one end of the milling tower where the clean wheat (or other grain) moisture content is adjusted to approximately 16%. The milling process is ready to begin. The flour milling process consists of the break system, purification or sizing system, the reduction system, and the tailing system. The mill tower usually consists of 4 to 7 levels with integral bins at each end of the tower. At one end are the tempering bins, and at the other end are the finished flour bins. Between the bin clusters are many levels housing the various systems that complete the milling process. The tower is

usually constructed from precast or slipform concrete. Sometimes smaller mills (which are part of a larger process) are constructed using only steel. The major elements of the milling process are discussed as follows:

The break system is primarily comprised of roller mills. In this system the wheels in the roller mills run in opposite directions at different speeds and have a saw tooth configuration. The purpose of the process is to separate the endosperm from the rest of the kernel. To achieve this, the wheat is run through the roller mills up to five times. As part of this process, sifters are also used to separate the endosperm from the bran and germ which is typically a co-product known as wheat feed.

The purification system consists of purifiers, roller mills and sifters. Purifiers sort particles based on size, air resistance, and specific gravity. The roller mills further reduce the size of the particles. Almost no flour is produced in this operation and the material is either passed to the reduction system or sent back to the break system. The purpose of the purification process is to separate the small bran from the endosperm. The use of purifiers is decreasing in modern mills due to cost effectiveness and efficiencies in other portions of the milling process, however.

The reduction system consists of a series of roller mills and sifters in sequence. The roller mills in this sequence are smooth, resulting in a finer grind. At this point it is desirable to have mechanical starch damage to the wheat to improve flour quality. This phase reduces the endosperm to flour. This process is repeated up to 11 times to obtain the fineness required for the flour.

The tailings system is where the unwanted co-products of the flour milling process go. The products are turned into animal or pet food. These co-products are often sent out in bulk. There are fewer tailings (or co-products) for whole grain flour, and more for white flour, because more of the kernel is used for whole grain flours.

In each of these systems the "overs" of each sieve (particles not fine enough to pass through a screen) are directed to another set of rolls (i.e. back through the process) for further reduction, or to one of the residue streams. At the end of the process the various runs of flour are blended and mixed to make the required grades of flour. They are then treated with the addition of malted barley, bleaching agents, enrichments, etc. before packaging or shipment in bulk.

There are two broad classifications of wheat: winter and spring. There are dozens of kinds of wheat, but in the US mainly Durham and Common wheat are grown. In the Pacific Northwest, a variant of wheat known as Club wheat is grown. Durham wheat is the wheat typically used in pasta production, including noodles and spaghetti. Common and Club wheat are used in the production of cake, cookie, pretzel, household, and other flours. Each type of flour is a combination of blends of different grinds of wheat.

Large mills have complex flows to control gradation to be able to produce multiple grades of flour. Other smaller mills are part of a vertical integration of a larger manufacturing process. For example, a Durham wheat meal may produce flour mixtures for the production of pasta. Another mill may be part of a bakery complex producing flour for bread or baked goods alone. Many mills will, however, produce wheat flour for consumer use.

The finished product bins are where the finished flour is stored prior to packaging or bulk shipment. The warehouse is where the packaging takes place. Warehousing typically consists of single story large square footage space, with loading docks and palletizing equipment. These structures are generally constructed from steel and metal panels or from precast concrete. Flour milling is a process that is governed by the FDA. All construction must be sanitary and easy to clean.

Utilities make the flour mill run, and air is a key system in a flour milling facility. It is used to convey flour from system to system, and to separate streams into components. Ten times as much air is required to move a single volume of flour. The air system consists of fans, blowers, compressors, and pneumatic conveying lines. Other elements of the air system consist of cyclones, dust collectors, and filters.

### Facility Area

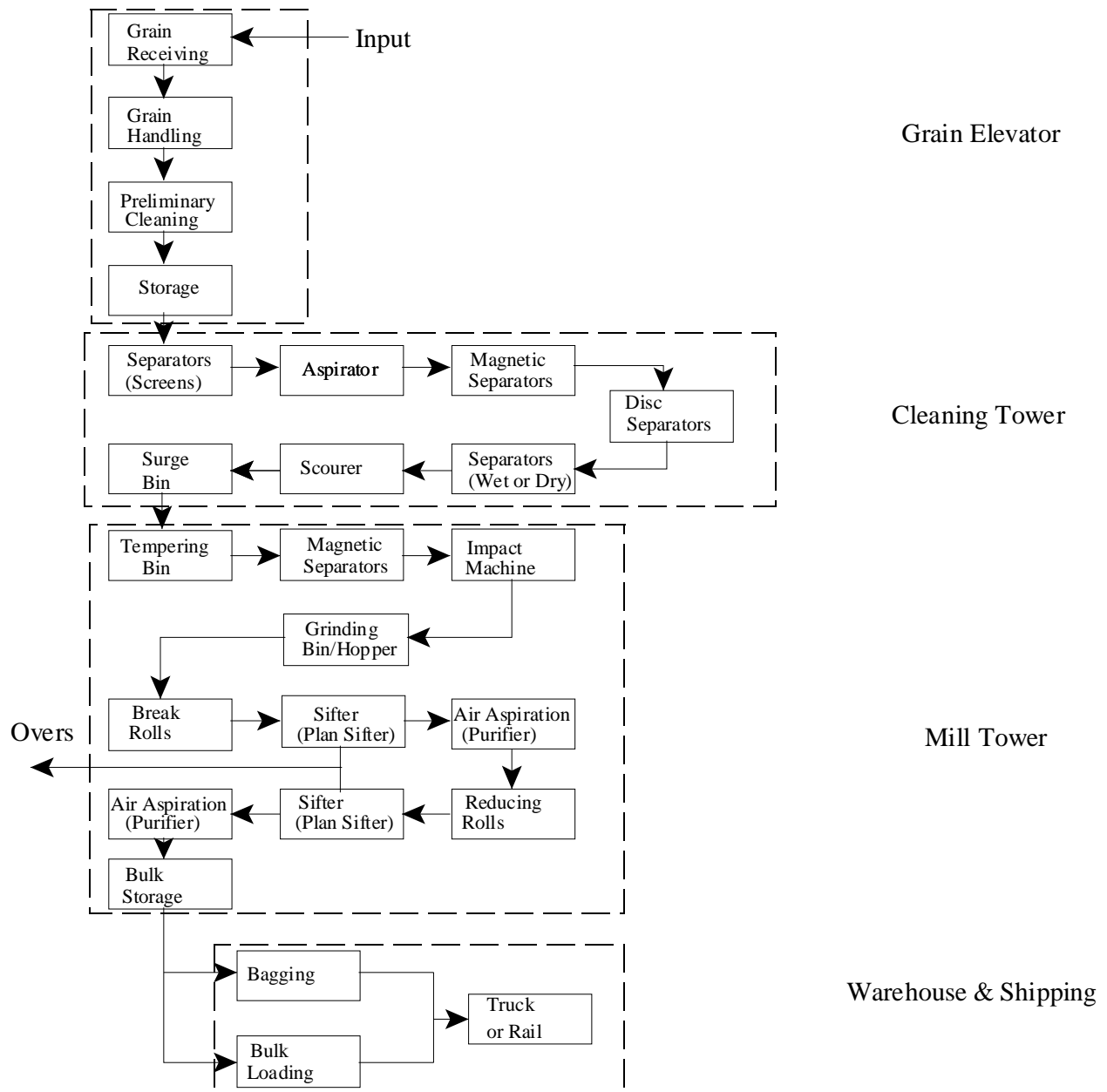


Figure 1. Flour milling block flow diagram.

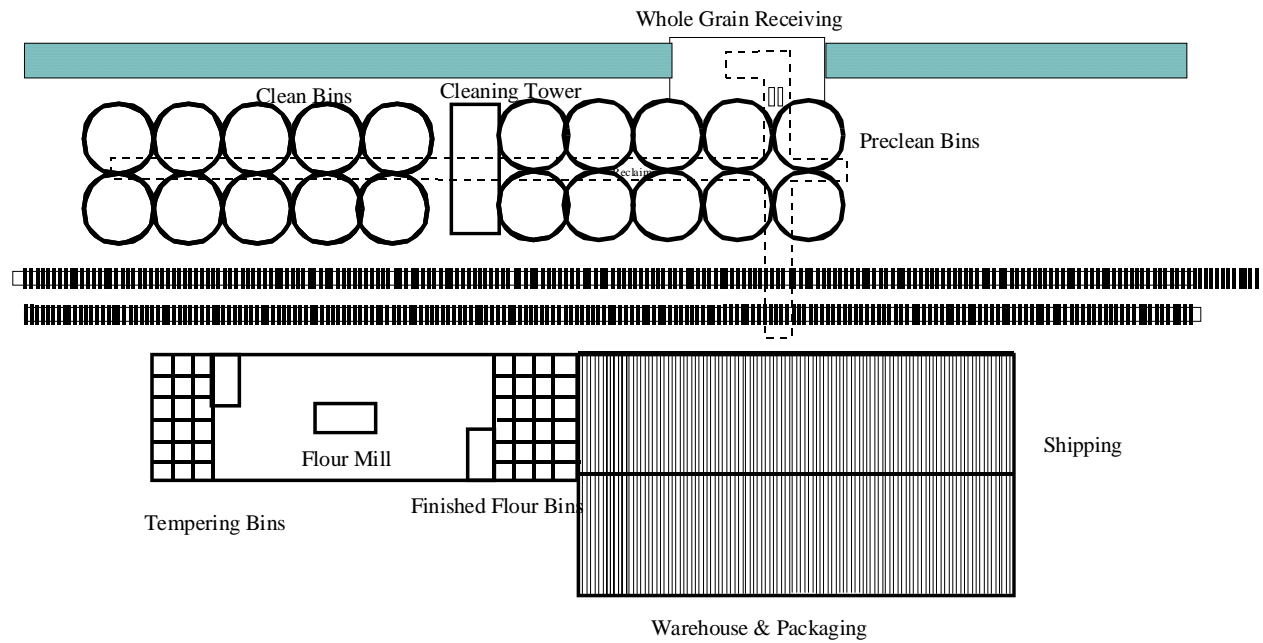


Figure 2. Flour milling facility layout.

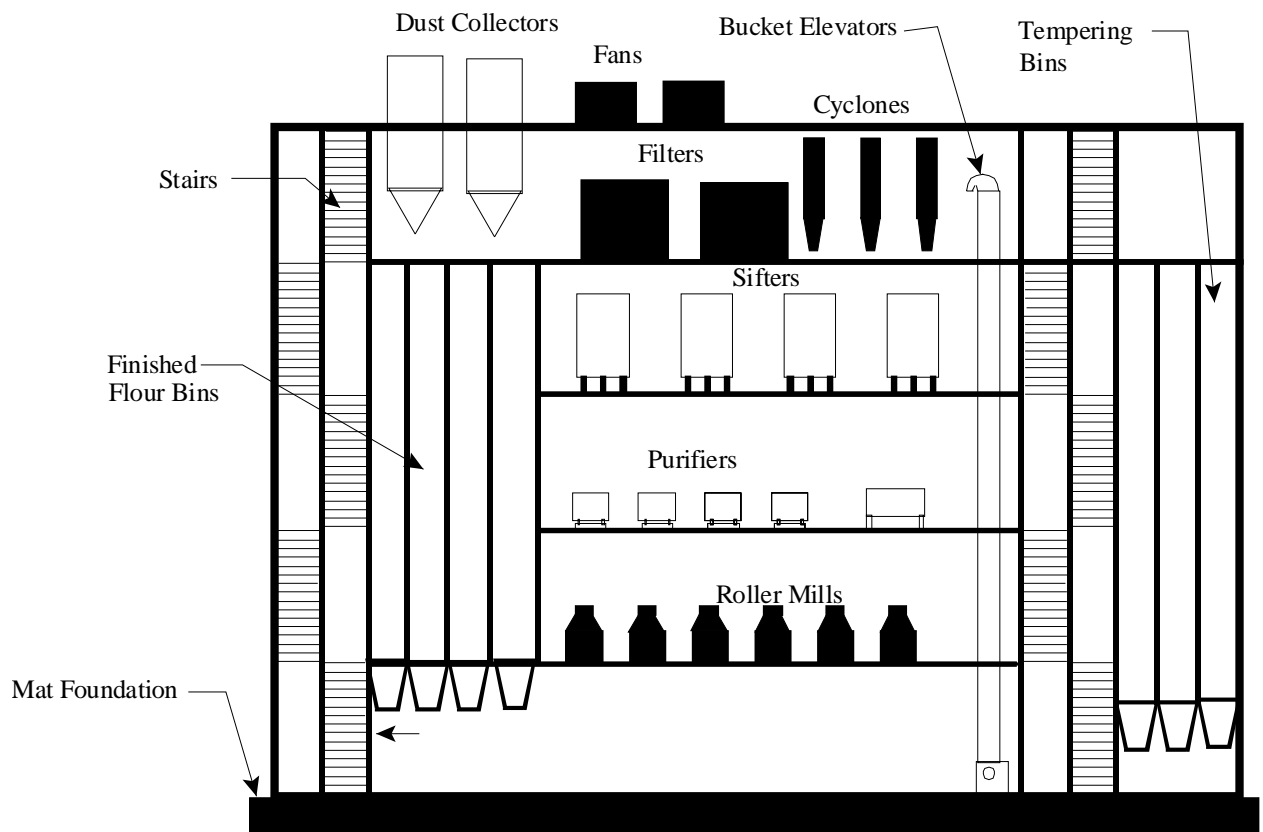


Figure 3. Cross section of a typical mill structure.

## Facility Planning

Proper planning is an important aspect of long-term profitability for a flour milling facility. It is important for engineers of these facilities to minimize these costs to increase value for owners and shareholders. A major part of effective planning is considering items such as (1) Long Range Planning, (2) Grain Supply, (3) Economic Factors, (4) Regulatory Issues, (5) Location/Site, and (6) Facility Expansion versus New Construction, (7) Technology, and (8) Facility Layout. Optimal planning should lead to lower life cycle costs. These are detailed as follows:

- **Long Range Planning.** Long range or strategic planning is a function of the strategic vision and objectives of an organization. It generally reflects the mission of the company and how it will proceed toward achieving its business objectives. For optimization of long-range profitability, capital spending on new facilities needs to reflect the strategic planning objectives of the organization.
- **Grain Supply.** The primary ingredient in the production of flour is wheat. Wheat production is dependent on a strong local farming community. To make flour, wheat will have to be shipped in or grown locally. The US wheat belt is located in the Great Plains and the Midwest States. Some wheat is grown in the Northwest. It should be noted that summer wheat tends to be grown in the northern states and winter wheat is grown in the southern states.
- **Economic Factors.** Economic considerations for the operation of a facility can have a major impact on its profitability. Local issues such as grain types and volumes produced in a particular geographic location, the availability of transportation, and the number of existing facilities in a particular geographic area will directly affect the economic success of a flour milling facility. Global economic issues, such as long-term increases in population, which in turn can increase demand, can also be a consideration. Additionally, the eating habits of the demographic population or the processing capabilities of regional industries may have an influence on production demand. Finally, Return on Investment, or ROI, should be a major consideration in the decision to operate a new facility.
- **Regulatory Issues.** Governmental and political issues can have a significant effect on the need for a facility in a particular region. Issues such as Good Manufacturing Practices (GMP) and identity preservation can have a major effect on international demand for products. Inside the United States, there are a number of regulations from both the EPA and FDA that can influence the design and operation of a flour milling facility.
- **Location/Site.** Selection of an appropriate site is an important consideration for the profitability of a flour milling facility. Locations close to applicable transportation and infrastructure are essential for facility operation. Functional rail facilities are essential for most flour milling operations. Appropriately rated roads and highways are also essential for all operations with truck traffic. When searching for a new site the owner needs to consider the bearing capacity of the soil. On a sufficient site with good bearing capacity, pressures expected under the grain storage facilities can approach 6000 psf. Pressures under the mill can exceed 4000 psf. Additional site issues can include drainage, wetlands, water and other similar items can come into play.
- **Facility Expansion vs. New Construction.** Once a decision has to be made to build a facility in a specific geographic region, the owner and engineer must examine if a currently existing facility in the area can be expanded or upgraded first. If the discounted cash flow of the cost of the upgrades is greater than new construction then consideration should be given construction of a new facility.

- **Technology.** Like all industries, the flour milling industry is an evolving industry with changing technology. Senior management and engineers must be aware of new technological trends being developed within the industry. As technologies shift, companies must be flexible and make changes when they are appropriate.
- **Facility Layout.** Facility layout and design is a key consideration in the operation of a functional facility. The relative location between physical locations of the receiving and load out, or the possibility for double duty, can play a role in the operational costs of running the facility. The type of construction and the amount of available land can have major role in the physical layout of the facility. For example, a loop track for a 110-car rail shuttle loading system can require a vast amount of land. Issues such as explosion or fire safety can influence the physical layout of a facility as well. Finally, the budget that the facility owner has available can dictate the types and sizes of construction that can be pursued, and can place severe restraints on the design of the facility. Additionally, the layout of individual pieces of equipment can have an effect on the total labor and power requirements of the facility.

## **Detailed Facility Layout**

After a flow diagram showing major unit operations is developed by the process engineer, the layout of the plant must be worked out, concurrently, by the process and building design engineers. The key to successful design of any process facility should involve the total integration of building layout and process unit operations. This first begins by laying out the major process equipment and bins. The process engineer then designs the secondary process systems layout. Simultaneously, the building engineer roughs out the building layout based on the major unit operations taking into account engineering and building code limitations. Providing an enclosure for the unit operations and sufficient space for access and maintenance are key for layout of the processing facility. Human occupancy considerations, although important, are secondary and are usually a cursory design review for most types of agri-industrial facilities such as flour mills.

Buildings in a facility will be separated by major unit operations and flow of materials. The engineering team should examine the block flow diagram to determine which unit operations go together (e.g., figure 1). Areas of each building should be arranged to minimize the transport of materials and should consider the optimal flow of materials. Additionally, the buildings should accommodate major vessel and equipment locations and have sufficient floor and headroom space for mechanical and process piping as well as electrical conduits. The designer should plan to have adequate work, utility, welfare, admin, and maintenance areas in the facility as well. The block diagram in Figure 1 shows the major areas of the facility.

When planning and laying out a facility it is important to minimize the physical need for mechanical conveying. One way to do this is to take advantage of gravity flow. Machines also must be laid out with adequate clearance for access, maintenance, and compliance with safety and building code requirements. Additionally processing machinery should be laid out with utility access considerations. For example a central chase for air or electrical may be required to service the equipment. Past studies have indicated that a mill volume of 60 to 70 ft<sup>3</sup> per hundred weight of annual production is typically required for a functioning mill facility (Posner and Hibbs, 2004).

## Life Safety Design Considerations

Once the layout has been determined by the owner and engineers, the facility detail design can begin. One of the first steps is application of the life safety codes. They are administered at state, local, and federal levels. Federal regulations, such as Occupational Safety and Health Administration standards from Title 29 of the US Code of Federal Regulations (NARA, 2004), and state-adopted model codes, such as the International Building Code (ICC, 2003a) dictate, in part, how facilities are planned and constructed. Highlights of these codes, as related to flour mill processing facilities, are discussed in the following sections. In this section a number of common elements related to life safety design will be discussed. Additional information can be found in Williams and Rosentrater (2004a&b).

### ***Model Building Codes***

The main building code in the United States is the International Building Code (IBC) (ICC, 2003a). The IBC defines a number of life safety and fire code related issues including occupancy types, construction types, height and floor area, egress, location on site, and a number of other major building layout issues. Minor details of construction such as stairs, guardrails, and equipment access platforms are detailed in the building codes. Some of the major items of consideration in the IBC are summarized in the following subsections. The reader should note that these discussions are not necessarily all inclusive, and they should consult the building code and other references for further details.

### Occupancy Classification

Chapter 3 of the International Building Code (ICC, 2003a) specifies ten major Use and Occupancy Classifications for buildings and facilities. For specifics, the reader is referred to the IBC, but these categories range from residential to hazardous industrial. Each of the major occupancy types are further subdivided by hazard or use. Occupancy in combination with fire rated construction is used to define allowable heights and areas of buildings. Occupancy loads are defined in table 1004.1.2 of the IBC and are detailed in table 1 for flour mill production facilities. Common Use and Occupancy Classifications typical for flour mill production facilities include:

- Group B - Business - The business, office and administrative areas of a flour mill facility usually fall under this occupancy classification.
- Group H - Hazardous – Hazardous processing areas with a risk of explosion or store or contain materials that have health hazards fall under the classification. Storage for agricultural commodities that shed substantial levels of fine dust falls under sub category H-2. In a flour mill processing facility, the raw grain storage silos and processing areas are usually classified as H-2. Under the appropriate conditions, grain and flour dust can be highly explosive.
- Group F - Factory and Industrial – Non-hazardous building processing operations would fall under this category. Examples include further processing that does not produce explosive dust such as packaging or cooking operations that exist in many agri-industrial facilities. These areas are usually classified as category F-1.
- Group S – Storage – Generally this classification is used for the noncombustible storage of products. Buildings or areas that store non combustible products fall under this category. Storage of non bulk flour may fall under this occupancy classification.

Once an occupancy classification is determined then fire rated construction type, height and floor areas can be determined.

Table 1. Occupant loads for flour mill process facilities.

Area	Square feet per occupant	Comments
Office and administrative areas	100	General office areas housing accounting, administration, and visitor reception.
Process areas	100	Areas housing major processing operations would fall under this category.
Storage or warehouse areas	500	Grain storage or warehousing areas would fall under this category.

## Height and Floor Area

Table 503 of the International Building Code (ICC, 2003a) defines the allowable height and areas of buildings of various fire rated classifications and occupancy types. These values can be modified based on lot frontage and the presence of fire sprinklers. As previously discussed the various areas of a flour mill production facility are likely to be Type I, or II construction with occupancy classifications that could include: F-1, H-2, B, or S-1. Type I construction allows for greater heights and floor areas relative to type II (Unlimited in some instances). Two sections of note include section 503.1.2 and section 507 which discuss unlimited area provisions of the building code. In particular, section 530.1.2 of the 2003 IBC allows for low hazard industrial processes that require large areas that accommodate crane ways or special machinery are allowed to be exempt from the height and area limitations in table 503. Section 507 provides additional exemption for manufacturing and processing applications can be unlimited if they meet certain frontage or fire sprinkler arrangements. The reader should consult the building code for specifics. Anytime these provisions are considered they should be coordinated with building code officials early in the project.

## Egress

Once the occupancy type and occupant loads are determined the design engineer can determine the number of exits, total required egress width and check the maximum travel distance within each structure. Table 1005.1 of the IBC (ICC, 2003a) defines the amount of egress width per occupant. Minimum egress width is 32 inches as defined in section 1008.1.1. Egress travel distances are defined in section 1015 and in Table 1015.1. The number of exits required are described in section 1018. Table 1018.1 describes the number of exits required per given occupant loads. Section 1013 describes common path of egress travel distances.

## Fire Rated Construction Requirements

Construction type combined with occupancy defines allowable height and area of buildings in a facility. Chapter 6 of the IBC (ICC, 2003a) defines four major construction types. These vary from a highly protected Type I construction to the least protected Type V construction. They are

further divided into subcategories of A and B, which define additional levels of fire protection. Generally, construction Types II and I consist of masonry, steel, and concrete structures. Type III construction has noncombustible exterior walls and interior materials of any material (e.g. timber). Type IV construction, heavy timber, is not commonly used in agri-industrial construction anymore. Type V construction is construction where any combustible or non-combustible material is used for construction and is applied to construction types that do not qualify for Types I to IV construction. Construction type determines fire ratings which are influenced by many other areas of the life safety planning for the facility.

Chapter 7 of the IBC discusses specific aspects of fire-resistive-rated construction. Fire-resistive-rated construction procedures give the design engineer the details to obtain the fire ratings required in chapter 6 of the IBC. Specific elements that the engineer must examine include horizontal elements such as floors and roofs (IBC section 711) and vertical assemblies such as fire walls (IBC Section 705), exterior walls (IBC section 704), fire partitions (IBC section 708) and barriers (IBC section 706). Additional discussions of shafts (IBC section 707), penetrations (IBC section 712), and smoke barriers (IBC section 709) are made in chapter 7. Finally, section 721 of chapter 7 discusses the calculation of the individual resistances of fire rated assemblies. Table 302.3.2 describes the fire wall ratings required for separation of occupancies and table 602 describes fire-resistance rating requirements for exterior walls based on fire separation distance and/or location on site. Additional information on the calculation of fire resistant elements is provided by the American Society of Civil Engineers in ASCE 29-99 entitled "Standard Calculation Methods for Structural Fire Protection" (ASCE, 1999). For specifics, including other additional requirements, the reader is referred to Chapter 7 and other relevant sections of the International Building Code (ICC, 2003a) and the International Fire Code (ICC, 2003b).

## Mezzanines

Occasionally, flour milling facilities contain mezzanines. For example, the warehouse may have an area with a mezzanine. Section 505 of the IBC (ICC, 2003a) discusses mezzanine design and construction. In general, it states that a mezzanine should not be counted as part of the floor area associated with the mezzanine. Additionally, it shall not cover more than 1/3 of the floor area of the room it occupies for purposes of building classification. Similar to other areas of the building, a mezzanine is required to have two independent means of egress.

## Industrial Equipment Platforms

Equipment access platforms are a special form of a mezzanine and are discussed in section 505.5 of the IBC (ICC, 2003a). In general, the total of all equipment platforms should occupy less than two-thirds of the building area at each level, and for purposes of occupancy classification shall not added to the floor area of the building. Access equipment that is attached to the platform such as stairs, ladders, walkways, and similar access shall not serve as part of the egress system for that building level, but still must comply with IBC and OSHA requirements for construction.

## Building Envelope and Energy Usage

Commercial building envelope design for thermal resistance, air leakage, and environmental conditioning of structures is governed by the International Energy Conservation Code (ICC, 2003c). The IECC references ASHRAE 90.1 (ASHRAE, 1999) as the governing document when calculations are made. Although most industrial buildings are exempt from the IECC, it is good business practice to minimize energy use for businesses, including process plants.

Required heating, cooling, and ventilation load requirements can be determined from ASHRAE Handbook of Fundamentals (ASHRE, 2001) or the ASHRAE Systems and Equipment Handbook (ASHRAE, 2000). A common problem in industrial process buildings is excess heat. This may require exhaust fans or ventilation. Excess heat may be recovered for additional use in processing operations or discharged using cooling towers. Proper planning and design of these systems can have a major influence on the building envelope design. Ventilation design is discussed in chapter 4 of the International Mechanical Code (ICC, 2001c) and moisture requirements are covered in chapter 12 of the International Building Code (ICC, 2003a).

For all buildings, the wall envelope must satisfy good thermal and moisture control. Chapter 14 of the IBC (ICC, 2003a) describes the thermal and moisture requirements of the building envelope. This chapter indicates that facility elements built to chapters 19 and 21 (masonry and concrete construction) of the IBC automatically satisfy the thermal and moisture requirements of this chapter. Wall or other building elements built to this standard must be moisture resistant. A tight building envelope is also required to maintain positive pressure in a building which is a key component of an effective sanitation program.

## Fire Protection Systems

The use of active fire protection systems in industrial facilities such as flour milling facilities can be used to increase allowable floor area or height as described in the various sections of the IBC. Type I construction typically does not require sprinklers for large areas. Other times, fire sprinkler systems are required for unlimited area single story buildings as discussed in the height and floor area section. The need for fire sprinklers is highly dependant on the type of fire rated construction. Individual insurance underwriters often have particular requirements for sprinklers. Design of fire protection systems is discussed in NFPA 13 (NFPA, 1999b) and the International Building Code (ICC, 2003).

## ***Government Regulations***

Government regulations are administered on a state and federal levels. They have a significant influence on the design and construction of a food production facility. Two sets of regulations which drive the design and construction of flour milling facilities include OSHA and FDA regulations.

### OSHA

OSHA standards are set out in Title 29 of the Federal Code of Regulations (NARA, 2007). These standards set workplace safety, and are considered a minimum that must be met for non-public operational areas of facilities. They cover a number of construction related issues such as access, exits, fixed ladder construction, stairs, ships ladders, guardrails, equipment access, and tunnel construction. Most items relating to constructed facilities are in section 1910 of Title 29 of the Code of Federal Regulations. OSHA standards are also of significant importance to facility operators as they influence a number of operational items relating to worker safety. OSHA standards are only utilized during design if more stringent than the governing building code.

### FDA

Title 21 of the Federal Code of Regulations discusses the requirements of food related operations. In particular part 110 of Title 21 (NARA, 2007) which is entitled "Current Good Manufacturing Practice in Manufacturing, Packing, or Holding Human food" has a number of

generic requirements for the design and construction of food production facilities. In particular, section 110.20 discusses the plant and grounds. In this document they note that:

- **Site.** Yards and lots adjoining the food processing facility should be maintained so they are not a source of food contamination. This includes keeping shrubs away from the building. Additionally the storage of waste must be in appropriate areas and the parking lot must be constructed in a manner to prevent food contamination. The parking lot must also be laid out in a manner such that it is well drained. Care must be taken in the layout of facilities to prevent sources or habitat for infestation.
- **Building.** The FDA requires that the building be constructed in a way such that floors walls and ceilings can be easily cleaned. Floor drains should be provided in wash down areas. Ducts and pipes must be located where they cannot contaminate food from condensation or falling debris. Adequate space should be provided between equipment and walls for cleaning. Materials of construction must be selected that are durable and easy to clean. These requirements directly influence sanitary construction methods. The reader is referred to the sanitary construction section for details.
- **Utilities.** A facility must maintain an operating system for waste treatment. There must be a potable water supply and adequate plumbing. There must also be a suitable dry and wet waste disposal system depending on the processing method. Subsequent to that rubbish and offal disposal must be provided for. Adequate toilet and hand washing facilities must be provided for employees.
- **Lighting and ventilation.** The FDA requires that adequate ventilation and control equipment are in place to minimize odors and vapors (including steam and noxious fumes) in areas where they may contaminate food. It also requires that fans and other air-blowing equipment are located in a manner that minimizes the potential for contaminating food, food-packaging materials, and food-contact surfaces.

Section 110.35 of Title 21 also describes a number of operational items that need to be considered during design to provide maximum functionality for the physical plant. These include:

- **Sanitation.** Other operational aspects that need to be considered during the design and layout of a flour milling facility include items such as cleaning/sanitizing of physical facilities, utensils, and equipment. Storage of cleaning and sanitizing substances is a concern requiring cleaning area to be designed in an appropriate manner. Layout of the facility for sanitation is a big concern. Pest control programs are also a major concern.
- **Maintenance.** Because food production facilities are harsh environments, design for maintenance and repair is essential. The FDA requires that all food production facilities be kept adequately clean and kept in good repair. Additionally, drip from condensate from ducts, pipes and fixtures should be avoided by placing drip pans underneath the piping or placing them in a USA space.

### ***Supplemental Codes and Standards***

The International Building Code specifies that specialty facilities must incorporate a number of additional special design provisions. Chief among these is the National Fire Protection Association (NFPA) documents as follows:

- **NFPA 68 – Guide for Venting of Deflagrations (NFPA, 1998a).** This standard relates to the design and installation of devices and systems to relieve pressures and gasses that result from explosions. This document includes information on the calculation of explosion

pressures and venting of these pressures. This standard relates to a number of industries, but is commonly used in the feed and grain industry to determine bucket elevator venting as well as venting for silos or structures that contain or process powder-like agricultural substances such as flour. Theoretically, the relationship between a gas and pressure is given by:

$$PV = nRT \quad (1)$$

Where:

P = is the absolute pressure (Pa)

V = is the volume (m<sup>3</sup>)

n = number of moles

R = universal gas constant (8.3145 J/mol K)

T = is the temperature (K)

From this relationship and empirical measurements developed from research, the following relationships were developed. First among which is effective diameter for non-circular cross sections:

$$D = 2 \left( \frac{A^*}{\pi} \right)^{1/2} \quad (2)$$

Where

D = effective diameter of silo, bin, duct, or other area (m)

A\* = Cross sectional area of silo, bin, duct, or other area (m<sup>2</sup>)

The area of a vent for an area experiencing deflagrations is:

$$A_v = 8.535 \times 10^{-5} (1 + 1.75 P_{stat}) K_{stat} V^{0.75} \sqrt{\frac{1 - \Pi}{\Pi}} \quad (3)$$

Where the following are defined as

A<sub>v</sub> = vent area (m<sup>2</sup>)

P<sub>stat</sub> = Static burst pressure (bar)

K<sub>stat</sub> = deflagration index (bar-m/sec)

V = Hazard volume (m<sup>3</sup>)

P<sub>red</sub> = reduced pressure after deflagration venting (bar)

P<sub>max</sub> = maximum pressure of a deflagration (bar)

$$m = P_{red} / P_{max} \quad (4)$$

For L/D values greater than 2 and less than 6 the vent area is increased by adding vent area ΔA. Which is defined as follows:

$$\Delta A = 1.56 A_v \left( \frac{1}{P_{red}} - \frac{1}{P_{max}} \right)^{0.65} \log \left[ \frac{L}{D} - 1 \right] \quad (5)$$

Where:

L= enclosure length or height (m)

The reader is referred to NFPA 68 for specific examples and data.

- NFPA 69 – Standard on Explosion Prevention Systems (NFPA, 1998b). This standard details the design, construction, operation, maintenance and testing of systems for the prevention of deflagration explosions. This document covers the prevention of explosions by the following methods: (a) control of oxidant concentrations, (b) control of combustible concentrations, (c) explosion suppression, (d) deflagration pressure containment, and (e) spark extinguishing systems.
- NFPA 61 – Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Products Facilities (NFPA, 1999). As the name implies, NFPA 61 is a standard that relates to dust explosion safety in agri-industrial process facilities that handle bulk materials. This document covers construction requirements such as egress, interior wall construction, building fire protection, and equipment, including dryers, venting, heat transfer operations, dust control, pneumatic conveying, and building fire protection.
- NFPA 85 – Boiler and Combustion Systems Hazards Code (NFPA, 2004). This document applies to the design, installation, operation, training, and maintenance (as related to safety issues) of combustion systems, including single burner boilers, multiple burner boilers, and atmospheric fluidized bed boilers.

## Building Design Considerations

### Overview

Once the engineering team has determined the process layout, the functional process areas, and the functional building layout, the building system detailing can begin. In this section descriptions of the loads for and design of the major elements of flour milling facilities will be discussed. As part of this discussion, major design standards will be referenced and key aspects will be highlighted. This is not intended to be an all inclusive discussion of all elements involved in the design process, but rather to highlight unique or significant aspects of the design process for flour milling facilities.

### Loads

Loads on flour milling facilities arise from a variety of sources, including wheat and its components, flour, roof and floor live loads, equipment (including dynamic loads), dead loads, and lateral loads such as wind and seismic forces. Flour milling facilities store large quantities of raw grain and finished flour products in both bulk and bag form. Material handling characteristics and flow properties for common ingredients in the flour milling process are provided in Table 2. Before an actual structural analysis and design is undertaken, the loads on the total system must be determined. Items such as structural tower weights, equipment weights, snow, and floor and roof live loads must be determined. This information can be gleaned from equipment vendors and from the building code documents such as ASCE 7-02

“Minimum Design Loads for Buildings and Other Structures” (ASCE, 2002). Section 16 of the International Building Code (ICC, 2003a) contains at length discussions of loads, and in particular Table 1607.1 describes a number of uniform distributed loads for a number of uses and occupancies. Additionally, bulk solids loadings for grain or other materials must be determined using ACI 313 “Standard Practice for Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials” (ACI, 1997) or ASAE EP 433 “Loads exerted by Free Flowing Grain on Bins” (ASAE, 2001). Details of granular loads are also discussed in Williams and Rosentrater (2004a).

Table 2. Estimated physical properties of grains and flour essential for structural design.

Commodity	Density (lb/ft <sup>3</sup> ), $\gamma$	Angle of Internal Friction (°), $\phi$	Effective Angle of Internal Friction (°), $\delta$	Coefficient of Friction Against Corrugations, $\mu$	Coefficient of Friction Against Concrete, $\mu$	Coefficient of Internal Friction Against Steel, $\mu$
Wheat	52	20	26 – 32	0.44 - 0.61	0.47 - 0.62	0.32 - 0.58
Flour	40	40	23 - 30	N/A	0.6	0.30
Bran	20	40	35 - 45	N/A	0.5	0.4
Screenings and Dust	40	40	35 - 45	N/A	0.9	0.8

### ***Grain Storage, Reclaim, and Distribution Design***

Whole grain storage is a major component of a flour milling facility. Storage may be of either concrete or steel construction. Typical concrete silo diameters vary between 25 to 35 feet with heights between 100 to 120 feet. Corrugated steel bins can also be used as whole grain storage. Corrugated bins typically will be larger in diameter and squatter. Blending and grading capabilities are desirable in a bin layout. Whole grain silos should be designed so that that some level of sanitation can be maintained. For example, beams should be dust shedded and attention should be paid to access for sanitation and cleanout. In a flour milling facility, grain storage is often broken into two components: pre clean and clean silos. Wall construction should be free of pits, pockets and other finish defects to inhibit insect infestation. For concrete silos this means that the inside of the bin should be trowel finished. Steel silos should avoid ledges.

The engineer must carefully plan the structural elements, which include the foundation and reclaim tunnels, storage wall construction, roof systems, and equipment supports. These are discussed in Rosentrater and Williams (2004a). Foundation types include mat, ring, and pile type foundations which may be designed by conventional or numerical methods such as the finite element method. Tunnels and pits must be designed for surcharge loads from the silo in addition to any soil loads. Design of concrete elements is conducted according to ACI 318 “Building Code Requirements for Structural Concrete” (ACI, 2002). Foundation elements are designed using ACI 336 “Suggested Analysis and Design Procedures for Combined Footings and Mats” (ACI, 1988). Silo walls must be investigated for hoop tension, bending and shear in addition to vertical axial capacity. Eccentric discharge from silos cause bending and shear in silo walls. This must be accounted for in the design of the wall. Extensive details of structural

and planning design considerations of these elements are discussed in Williams and Rosentrater (2004a).

### ***Cleaning Tower***

Wheat cleaning towers are tall vertical structures that house cleaning equipment. They are usually constructed from concrete or steel. Height is important because they take advantage of gravity flow between the various cleaning unit operations. Cleaning towers are usually rectangular in shape and consist of 4 to 6 levels. Due to their height, most cleaning towers are constructed using slip form concrete methods, although it is possible to build a steel tower utilizing stick-built steel systems. Rectangular walls of slip formed towers are flat elements and are designed by chapter 14 of ACI 318 “Building Code Requirements for Structural Concrete” (ACI, 2002). Integral wall pilasters are designed as columns using chapter 10 of ACI 318 (ACI 2002). Design requirements for structural steel towers would follow the recommendations of the American Institute of Steel Construction (AISC, 1989) and the analysis of shell and plate elements would follow provisions in Timoshenko (1959). Sanitary details for both concrete and steel wall, ceiling, and floor elements are discussed in Imholt and Imholt (1998) and in the sanitary construction section of this paper.

### ***Tempering Bins***

Tempering bins are usually somewhat smaller concrete or steel bins that are used for storing whole grains in the clean and preclean bins. The shape of these silos can vary depending on the size and shape of the structure that contains them. For example, if the tempering bins are contained inside a slipformed mill structure, they are integrally cast in the tower and are typically rectangular in shape. If the bins are contained inside a steel mill, then it is likely that they will be round steel construction and separately installed in the mill. In other scenarios, slipformed concrete silos could be considered.

Tempering is the final grain conditioning prior to milling, and it often involves adjustment of grain moisture content. Bins that are used for tempering must be sanitary. Key design aspects for tempering include bin finish and flow type. All finishes must be smooth and free of pits or surface defects that could lead to unsanitary conditions. For example, concrete bins should be smooth floated without pits. Welded steel bins should be seam welded throughout. Another key element in the functional design of tempering is the use of mass flow. Mass flow occurs when the flow results in “first in first out” in the bin. From a sanitation standpoint this means that old grain is not mixed with new grain. From a structural standpoint mass flow can cause tremendous lateral forces (known as switching forces) at the transition between the hopper and the bin wall. Many methods exist for the determination of these switching forces but the most commonly used relationship is defined by Walker (1966):

$$q_y = \frac{\gamma}{n-1} (h_h - h_y) \left[ 1 - \left( \frac{h_h - h_y}{h_h} \right)^{n-1} \right] + q_o \left[ \frac{h_h - h_y}{h_h} \right]^n \quad (6)$$

Where

$q_y$  = vertical pressure (psf)

$h_y$  = depth below hopper (ft)

$h_h$  = height of hopper (ft)

$\gamma$  = weight per unit volume (lb/ft<sup>3</sup>)

$$n = \frac{2B}{\tan \theta} \text{ (but not less than 1) For circular cones}$$

$$n = \frac{B}{\tan \theta} \text{ (but not less than 1) For plane flow hoppers}$$

$$B = \frac{\sin \partial \sin 2(\theta + \beta)}{1 - \sin \partial \cos 2(\theta + \beta)}$$

$\theta$  = angle of hopper from vertical

$\partial$  = Effective angle of internal friction

$$\beta = \frac{1}{2} \left[ \phi' + \arcsin \frac{\sin \phi'}{\sin \partial} \right] \quad (7)$$

Where:

$\phi'$  = Angle of internal friction

Pressure normal to the hopper surface is given by the following relationship:

$$p_n = \frac{1 + \sin \partial \cos(2\beta)}{1 - \sin \partial \cos 2(\theta + \beta)} \quad (8)$$

Other aspects of bin design must be completed in compliance with generally accepted engineering design codes. Specifically, ACI 313 "Standard Practice for the Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials" (ACI, 1997) discusses design and construction aspects of concrete silo design. API 620 "Recommended Rules for the Design and Construction of Large, Welded, Low-Pressure, Storage Tanks" discusses elements of steel bin construction. Additional information about the construction of bins and tanks is available in Gaylord and Gaylord (1984) and Rotter (2001).

### ***Finished Flour bins***

Similar to the tempering bins, the finished flour bins are smaller sanitary bins of either square or round shape (figure 4). Slip formed bins tend to be square or rectangular and steel bins are typically round. Shapes can vary however. These bins hold the finished flour, which is typically pneumatically conveyed into the bin. These bins can be either steel or concrete construction, and must be mass flow in order to properly function. Because of the final nature of the finished product, these bins must be sanitary in construction. Finishes must be smooth, free of pits, ledges and other surface defects. Welds must not only be structurally strong, but must also seal all joints and connections. With pneumatic discharge and filling it is possible that the bin could develop internal pressures. Concrete bins are going to be designed according to ACI 313-97 "Standard Practice for the Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials" (ACI, 1997) and steel bins can be designed according to API 620

“Recommended Rules for the Design and Construction of Large, Welded, Low-Pressure, Storage Tanks.” (API, 2002). Other design information can be obtained from Gaylord and Gaylord (1984) and Rotter (2001).

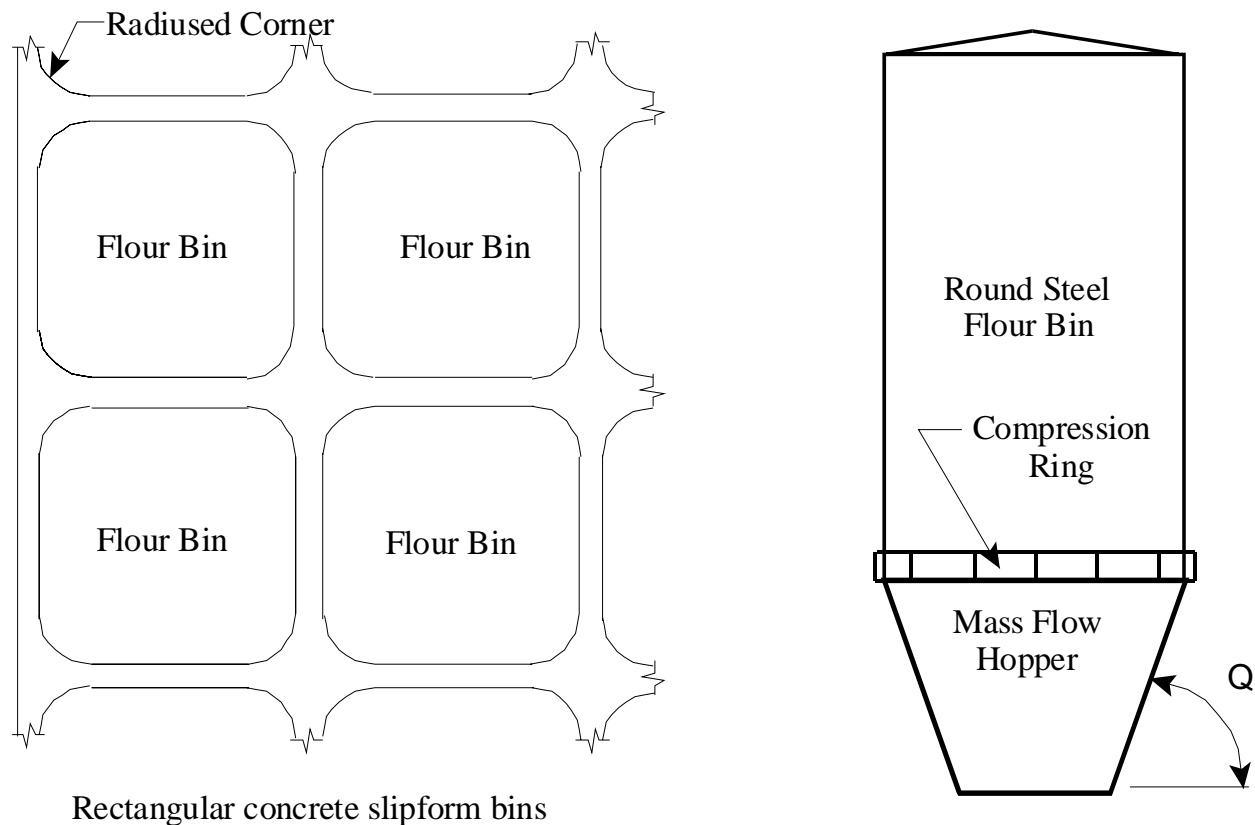


Figure 4. Flour bin types for steel and concrete facilities.

## Mill Construction

### Construction Methods

Both concrete and steel construction are used for the construction of the mill portion of a flour milling facility. Typically, large mills are constructed using precast and slipform concrete, or just slipform alone. Slipform construction consists of cast in place concrete walls that are extruded continuously over the entire height of the structure. Floors can be constructed using both precast and steel beams. Precast beams can be set during the slip form and steel beams are attached to inserts that are embedded during the slip form (figure 5). Floors can be topped precast or cast in place concrete which is set after the slip form is complete.

Sometimes the mill processing floors are constructed between the mill tempering and final product bins using precast elements. When this occurs beams are attached to slipwall inserts and supported by intermediate columns. Floor and roof elements are added to support the structure. Precast beams can consist of inverted tee, spandrel, and rectangular beams depending on the floor elements, which are usually hollowcore plank with a bonded structural concrete topping. All the elements are held up by precast columns. Double tees are usually used as structural elements for the roof, and the structure is enclosed by insulated precast wall panels which can be either a double tee or flat plate style construction. Built up roofing is then

applied over the roof system. For design of precast elements the reader is referred to the PCI design Handbook (1999).

Smaller, or mini mill, frameworks are usually constructed using steel construction. Some of the smallest mills are skid mounted and incorporated into a larger configuration. Other mills are constructed using piecemeal or stick type construction to form the structure. Typically, a structural steel configuration consists of closed tube columns and wide flange beams with bar joists. The walls are enclosed with insulated metal panels, although precast concrete can be used as the enclosure. When a bar joist ceiling is used, an insulated metal panel drop ceiling needs to be installed. Sanitary construction must be followed and could include curbs, enclosed shapes, and shedded beams. See the section on sanitary construction for further commentary.

Another design concern is floor vibrations and dynamic forces from the processing equipment. Care should be taken during the design of the floors for vibration. As a first step, the operating natural frequency of the equipment should be compared to the natural frequency of the floor. More than one natural frequency is possible, and so several modes will have to be investigated for each floor. When the natural frequency of the equipment and the floor match it is possible to have resonance. Dynamic forces will increase loading on supporting elements. An extensive discussion of vibrations and dynamics occurs in Clough and Penzien (1975).

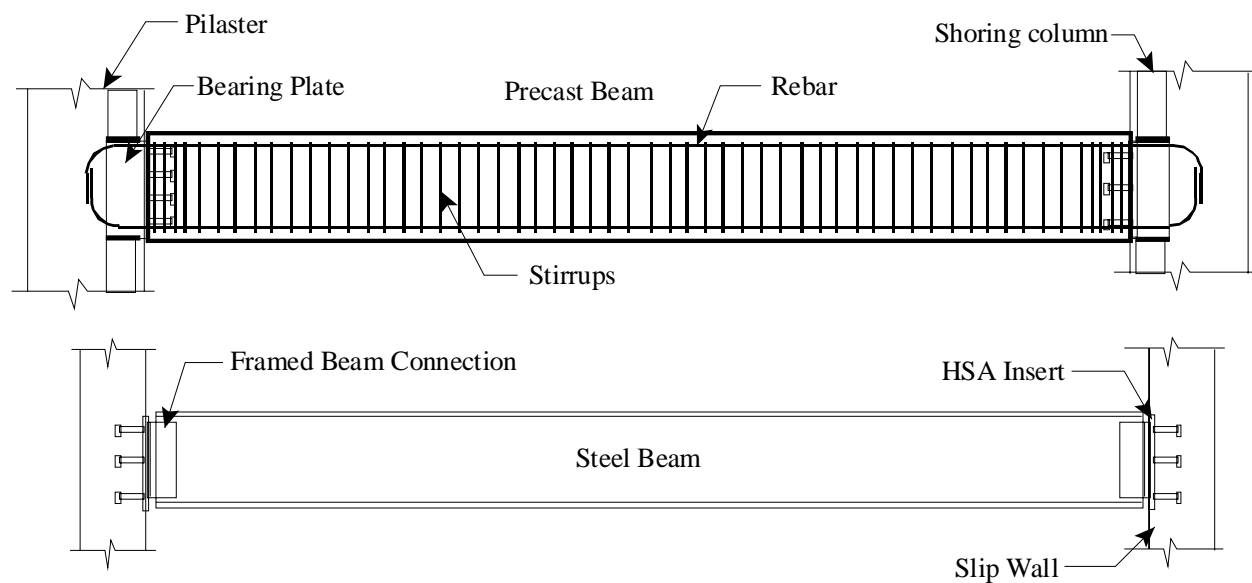


Figure 5. Typical floor beams for slip formed towers.

### Slip Wall and Bin Construction

Storage of tempered grains, flour, and co-products are accomplished using bins built integral to the mill structure (figure 4). Almost all mill towers are rectangular. Concrete mill structures are fairly large and the walls typically need stiffening using vertical wall pilasters that extend the entire height of the structure. Bins are constructed integrally with the outer mill shell, and extend about the upper portion of the tower. The basic wall thickness below the pressure zone is determined using the span-to-thickness ratios defined in chapter 14 of ACI 318 "Building Code Requirements for Structural Concrete" (ACI, 2002); bin walls span horizontally between the vertical pilasters (figure 6). As a large number of vertical mill towers are constructed using slipform construction techniques, the floors are not in place at the time of construction. Thus it

is common for the construction load case to control. Most design engineers consider the pilasters as the main vertical load carrying members and also use the pilasters to transfer lateral force (wind) in the floor diaphragms. Rectangular bins are designed for axial (tension), flexural, and shear forces using the provisions of ACI 318 "Building Code Requirements for Structural Concrete" (ACI, 2002).

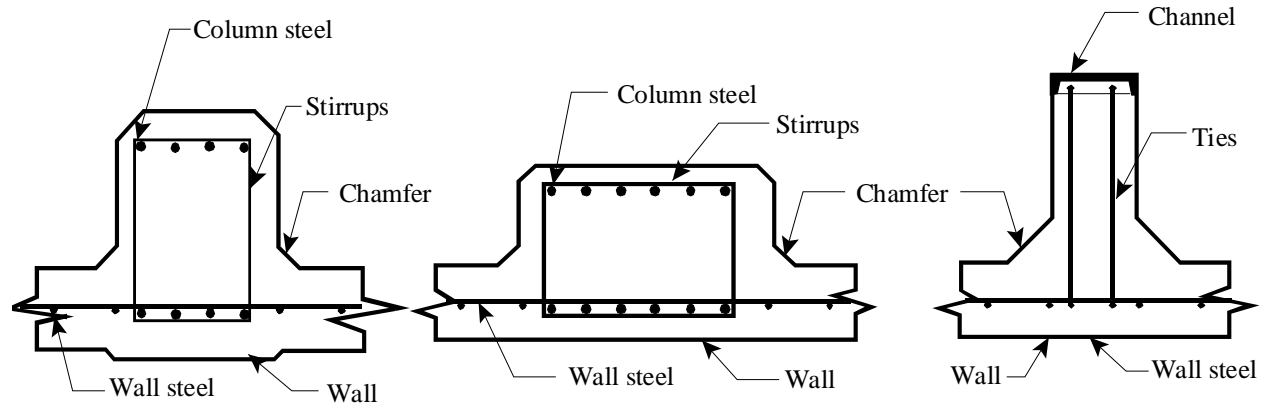


Figure 6. Typical slip form wall pilaster arrangements.

Steel bins and silos are often supported integrally with the mill structure. Rectangular and round bin design is discussed in Gaylord and Gaylord (1984) and Troitsky (1982). Rectangular bins primarily experience tension, bending and shear, and steel silos mostly experience hoop tension. Regardless of the bin shape, it is important to provide rings, stiffeners and other elements to provide the necessary strength and stiffness to each bin. Metal bin clusters are supported on large steel framework support structures with columns placed under the intersection of every second or third bin cluster. Transfer beams support the bins between the columns.

Eccentric discharge is an issue that design engineers of both concrete and steel rectangular bins have to contend with. Several methods for computing eccentric effects have been discussed by Williams and Rosentrater (2004b). Eccentric discharge must be considered in design when it occurs.

### ***Packaging and Warehouse Construction***

Once the wheat is milled and turned into flour it is stored in bulk and either shipped or packaged. In this section we will look at preferred construction methods for food grade warehouse construction. Food grade packaging and storage warehousing can be constructed from precast, tilt-up, or steel construction. Each has particular features that are discussed in the following paragraphs.

When structural steel construction is used, steel frames are often constructed using closed shaped tubes as columns. Primary beams are constructed from wide flange shapes and the secondary roof framing is of bar joist construction. The walls of these types of facilities are typically non-load bearing precast and tilt-up or alternatively, insulated metal panels. Standard metal building panels could be used, but insulated metal panels are preferred over standard metal building metal panels because of their greater cleanliness. For further sanitation, a USA space or suspended ceiling should be added to enclose any mechanical piping in the facility.

A precast warehouse usually consists of precast beams and columns with nonload bearing precast wall panels. Column and beam lines form the interior frame work. Inverted tee or ledger beams run over the columns and precast double tees are used for the roof construction. They typically used to span from beam to beam. Flat or double tee wall panels are used to enclose the wall (figure 7). Occasionally, wall panels can be load bearing. Curbing is added at the base of the wall where it attaches to the floor slab. Additionally, any ledger beam shelved should be filled with grout to form a slope to prevent dust and other materials from accumulating. Design should be done in compliance with the PCI Handbook (1999).

Tilt-up construction often involves the using exterior low rise bearing walls with interior steel beams. Bar joists and metal decking create the roof system. The bar joists bear on the exterior tilt-up walls and on the interior steel beams. A built-up roofing system is typically used over the metal deck construction. For details of tilt-up construction the readers are referred to the tilt-up construction handbook that is published by ACI (ACI, 1989)

As with all areas of the facility the warehouse must be constructed using sanitary materials and construction techniques. The reader should refer to the section in this paper on sanitary construction and coatings for base cove, wall joints, floor coverings and other relevant items. When laying out the warehouse, it should include offices, truckers lounge, and a loading dock areas to serve its basic areas.

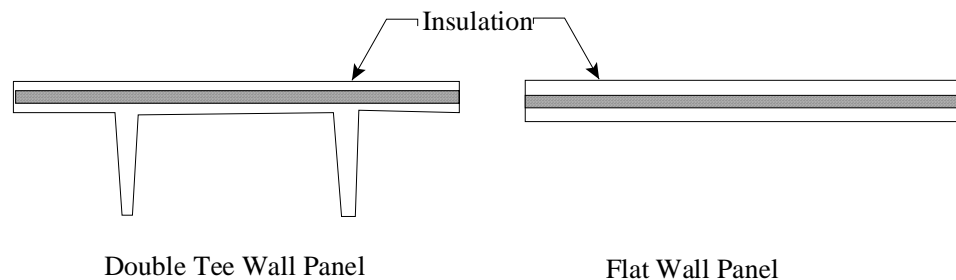


Figure 7. Typical insulated wall panel configurations.

### ***Sanitary Construction***

Food processing facilities such as flour mills are federally inspected food processing plants. As part of food production system they are governed by Title 21 of the Code of Federal Regulations (NARA, 2007) which is administered by the FDA. Although the food code is not specific to the exact nature of the requirements of construction, there are a number of practical detailing items that should be incorporated into a sanitary facility design:

- Coving or Curbing at bottom of walls. This is typically done by creating a concrete cove about 4 to 8 inches wide and at least 12" high. Coves in areas with forklift traffic have been constructed as high as 48" inches tall to provide additional protection to walls. (figure 8)
- Sanitary Shapes. Sanitary shapes can consist of both airtight sealed or completely open members. Structural members that support floors, mezzanines, platforms, and equipment need to be sanitary. Two schools of thought exist for this. If a member is sealed to be airtight then dust or moisture cannot get inside of the member. The other school of thought indicates is that if the member is open then can be easily cleaned. Experience by the author indicates that in dry processing facilities (such as flour mills) that closed shape members are better, but open shape members are more sanitary in wet facilities such as meat processing facilities. Ledges should be avoided if possible.

- Avoid dust ledges. Flat ledges should be avoided in all circumstances where dust and water accumulate. For example, exposed WF beams should have exposed ledges dust shedded with 60 degree seal welded plate. Another situation where shedding is desired is inverted precast tee ledges. In this case they should be grouted in such a manner that dust and debris does not accumulate on member horizontal surfaces.
- Eliminate Voids. Pockets and gaps between walls are areas where moisture, dirt, and pests can accumulate. All designs should avoid these conditions.
- Coatings. Wall coatings should be food safe and able to resist the multiple cleanings with harsh chemicals. Floor coatings should be slip resistant cleanable and abrasion resistant. Epoxy or urethane finishes work well as floor coverings. For paints and wall coatings epoxy based coverings are the norm but other coatings are possible. Epoxy paints on masonry, concrete and steel members are preferred. Sealers are preferred on exposed concrete.
- Caulking. Food grade caulking to seal all joints, connections, etc. where infestation can occur or water can penetrate.
- Finished product, Concrete or steel storage. Storage should be smooth or finished in a manner that is free of ledges, pits, or other areas where material can accumulate or pests can hide. Mass flow bins, which are usually used to improve flow, can be used to limit hang-ups.
- Openings. Doors jambs should be solid, tight fitting hardware, with no joints. All cavities should be sealed with expanded foam. Windows should be minimized and any sills should be sloped where they are used. Jambs, sills, and other areas should be solid with no voids.

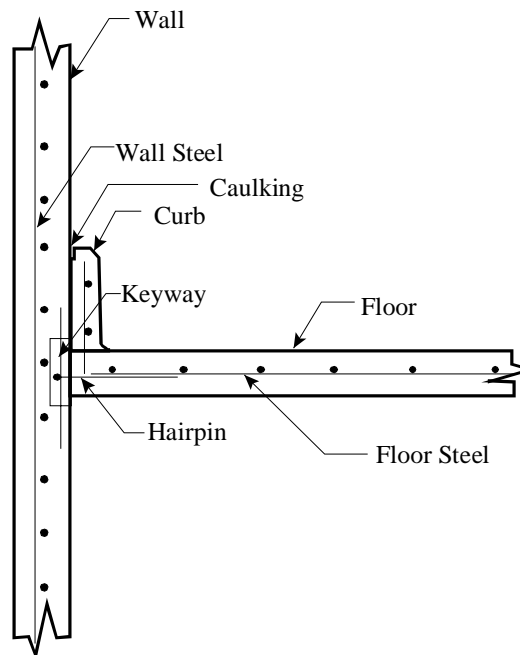


Figure 8. Floor wall junction showing sanitary curb construction.

## Summary

This paper summarizes design procedures related to the construction, planning, and operation of flour milling facilities. In particular, the life safety, layout, planning, and structural provisions were discussed. Toward that end, standards, procedures, and methods of design and construction were discussed. Both engineers as well as educators should find this paper useful.

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